DEAP/CLEAN: Detecting dark matter with liquid argon (and neon)

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Outline

Introduction
- Dark matter
- Dark matter and noble gases
- Scintillation in liquid noble gases

MicroCLEAN
- Calibrations
- Nuclear recoil scintillation efficiency
- Pulse shape discrimination

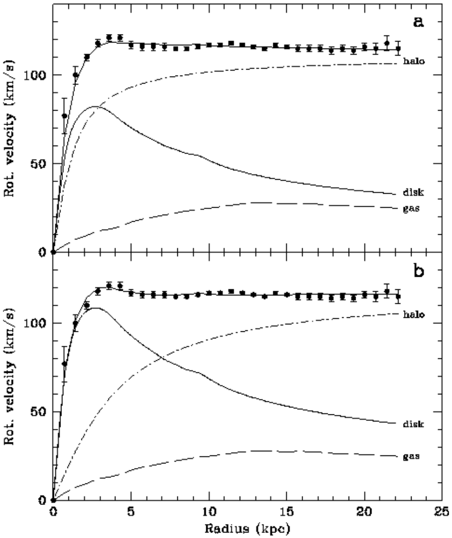
DEAP1
- DEAP1 on Surface
- DEAP1 Underground

Neon results
- Neon in MicroCLEAN
- Simulations with neon

Observational evidence

- Most physicists would agree that a large fraction of our universe, and the majority of the matter, is some form of “dark matter”
- The evidence for dark matter comes from a variety of sources at all scales
  - Galaxy rotation curves
  - Galaxy clusters
  - Gravitational lensing
  - CMB observations
  - Galactic collisions

Observational evidence



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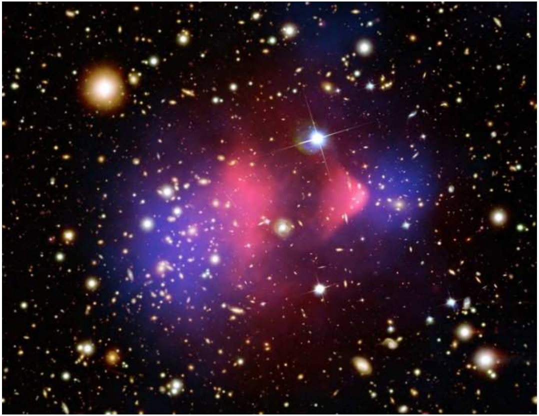

NASA:Markevitch et al., Clowe et al.

What is the dark matter?

- Most discussed candidate - Weakly Interacting Massive Particles or WIMPs
  - Produced during the Big Bang
  - Decouples from ordinary matter as the universe cools and expands
  - Would exist today with densities of about 1000/m^3
- A theoretical candidate comes from supersymmetry - neutralino
  - The lightest supersymmetric partner (LSP), with a mass 10 GeV $<$ m$_\chi$ $<$ 1000 GeV
  - The LSP is stable (by R-parity)
- Other candidates, e.g. Kaluza-Klein particles from universal extra dimensions

How do we find it?

- Indirect - Detect annihilation products from regions of relatively high density like the sun or the center of the galaxy
- Accelerators - create a WIMP at the LHC
- Direct - WIMPs can scatter elastically with nuclei, and the recoil can be detected directly

How do we find it?

- Direct - WIMPs can scatter elastically with nuclei, and the recoil can be detected directly
    - Like neutrinos, dark matter interacts very weakly with ordinary matter
    - The key to dark matter detection, like neutrino detection, is the energy threshold and backgrounds
    - The energy deposited by dark matter in an elastic collision is $\sim$10-100 keV
    - Can't use standard neutrino detector techniques
        - Water Cerenkov threshold is too high ($\sim$several MeV)
        - Liquid scintillators have ^{14}C backgrounds

Rate calculation

- The differential cross section (for spin-independent interactions) per kilogram of target mass per unit recoil energy is

$$\frac{dR}{dQ} = \frac{\rho_0}{m_\chi} \times \frac{\sigma_0 A^2}{2\mu_p^2} \times F^2(Q) \times \int_{v_m} \frac{f(v)}{v} dv \tag{1}$$

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    - Proportional to A^2 for most models

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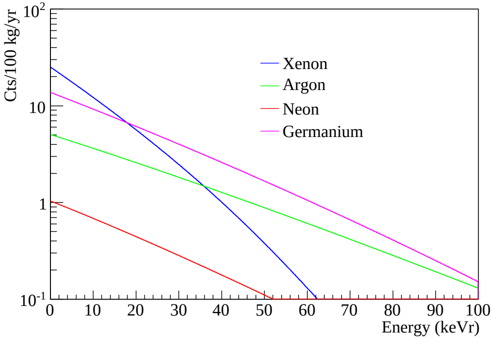
- The velocity distribution of dark matter in the galaxy - of order 30% uncertainty, and $v_m = \sqrt{Q/2m_r^2}$

Rate calculation

- Integrated rate above threshold, 100 GeV WIMP, $\sigma_0 = 10^{-45}$ cm^2

$$I = \int_{Q_{thresh}} dQ\, dR/dQ = \int_{Q_{thresh}} dQ \frac{\rho_0}{m_\chi} \frac{\sigma_0 A^2}{2\mu_p^2} F^2(Q) \int_{v_m} \frac{f(v)}{v} dv$$



Backgrounds to dark matter

Some standard radiation detectors

Geiger counter

Sodium iodide crystal

Germanium

Gamma ray interaction rate is proportional to
(# of electrons in detector) x (gamma ray flux)

Typical count rate = 100 events/second/kg = 10,000,000 events/day/kg
put it in a good lead shield ---> rate drops to 100 events/day/kg.

State-of-the-art dark matter detectors ---> sensitive to 0.01 events/kg/day

Where do backgrounds come from?

- Cosmic rays
  - Underground labs
- Radioactive contaminants, including radon
  - Purification systems
  - Radon-free air, surface cleaning, inert cover gases
- Detector materials - steel, glass, etc
  - Use radiopure materials, self-shielding
- The target itself?
  - Discrimination against different types of backgrounds

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“Noble liquid revolution”

- The most successful target has been germanium, and CDMS has the best limit to date
  - And events!!!
- Small detectors collect the heat and ionization released when radiation interacts in the germanium

"Noble liquid revolution"

- The most successful target has been germanium, and CDMS has the best limit to date
  - And events!!!
- Small detectors collect the heat and ionization released when radiation interacts in the germanium
- While successful, these detectors are difficult to scale
  - Current detectors consist of a few kg
  - Germanium is expensive
  - Fabrication and testing of the CDMS detectors are even more so

“Noble liquid revolution”

Why noble gases

- Relatively cheap, available, dense
- Easy to purify
- Emission of scintillation light when exposed to radiation e.g. 40 photons/keV for argon, comparable to common radiation detectors like NaI
- Discrimination capability between nuclear recoils that make up a WIMP signal and electronic recoils from most backgrounds
- Easily scalable (large targets, self-shielding)

In particular...

- Argon - all the advantages, but...
  - ^{39}Ar, a beta emitter at 1 Bq/kg
  - Or about 10^7 events/keV/100 kg/yr
  - Requires discrimination against electronic recoils at that level to eliminate ^{39}Ar background
  - Or depleted ^{39}Ar
- Neon - no radioisotopes, but...
  - Smaller cross section

WIMPs

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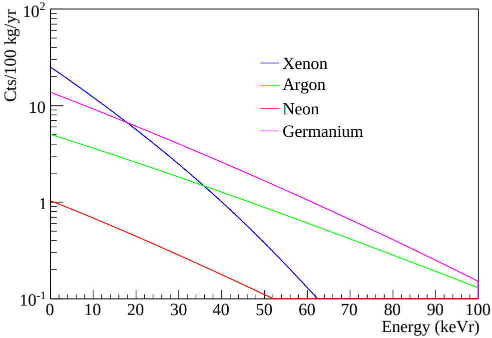
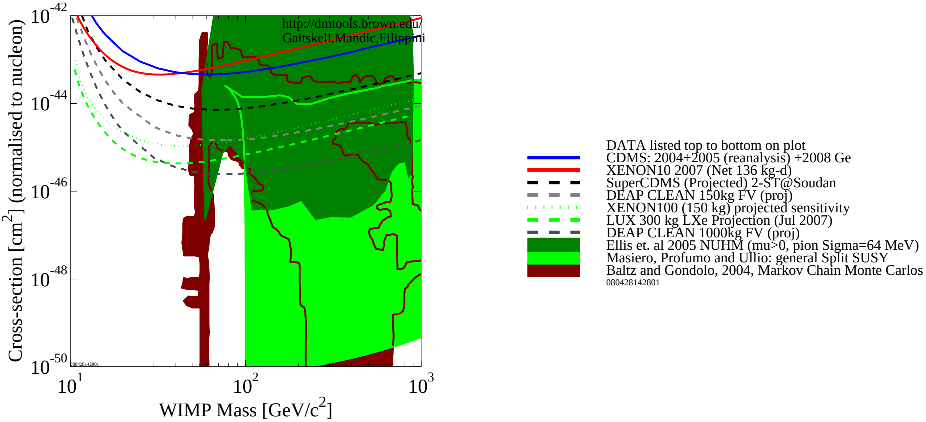


WIMPs

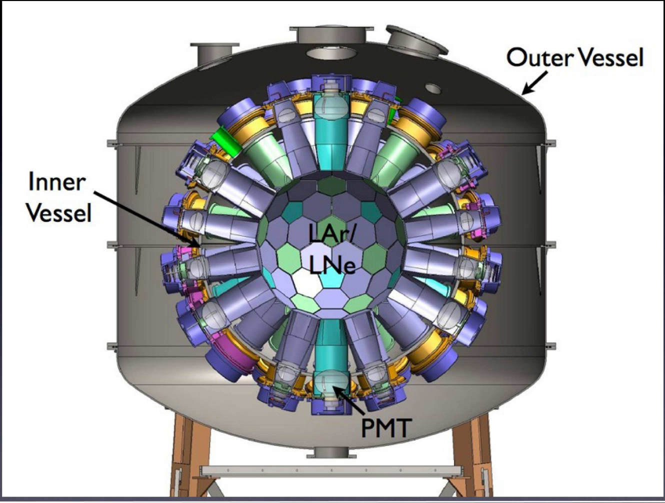


- If we detect WIMPs, require more statistics → bigger detectors
- If we do not detect WIMPs, require more sensitivity → bigger detectors

DEAP/CLEAN program

- Dark matter and neutrino detection with argon and neon
- MiniCLEAN - 500 kg of active volume (150-170 kg fiducial)
  - To be installed underground at SNOLAB in summer-fall 2010
  - Will run with both argon and neon
- DEAP3600 - 1 tonne fiducial
  - Recently awarded \$26.4M in funding jointly with SNO+, construction underway for commissioning at SNOLAB in 2011

The Detector



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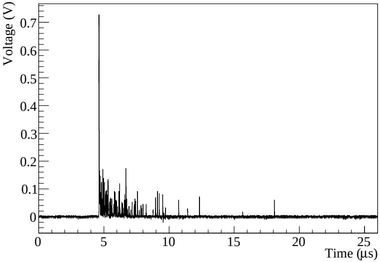
Scintillation in liquid noble gases

- Radiation (gamma, electron, neutron, WIMP) collides with electron or nucleus in the liquid and deposits energy
- The recoiling electrons or nuclei excite other atoms
  - The creation of Ar^* or Ar^+
  - Recombination produces more excited atoms, which join with other atoms to form Ar_2^* dimers
- Noble gas molecules are not stable and quickly decay, emitting ultraviolet photons
- In dual-phase detectors, one also collects the ionization

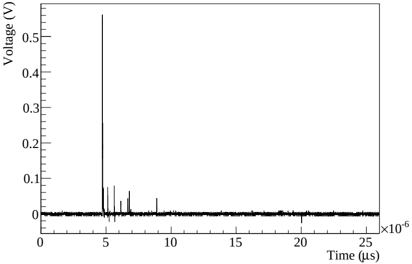
Scintillation in noble gases

- Two molecular states - singlet and triplet
  - Singlet decays very fast (ns in LAr and LNe) but the triplet decays slower (μs in LAr and LNe)
- Electronic and nuclear recoils produce different ratios of singlet to triplet molecules
  - The pulse timing allows you to discriminate between the two types of events - pulse shape discrimination (PSD)

Scintillation in noble gases



- Electronic recoil



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  - The pulse timing allows you to discriminate between the two types of events - pulse shape discrimination (PSD)
- WIMP signal would be nuclear recoils, most backgrounds (including ^{39}Ar) are electronic recoils
- In addition, nuclear recoils produce less light than electronic recoils - nuclear recoil scintillation efficiency or L_{eff}
  - PSD in combination with L_{eff} sets threshold of detector

What is to be done for DEAP/CLEAN?

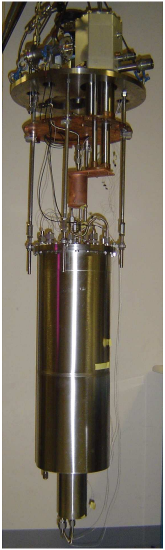
- Measure PSD in both argon and neon
  - Demonstrate that we can eliminate ^{39}Ar background
- Measure nuclear recoil scintillation efficiency, $\mathcal{L}_{eff}$, in both argon and neon
- Get a handle on backgrounds from Rn, etc.

Two prototype detectors

- MicroCLEAN at Yale
- DEAP1 at SNOLAB

MicroCLEAN

- Small, 3.14 liter detector designed to optimize light collection
- Goals:
  - Measure PSD down to low energies relevant for a dark matter search
  - Measure nuclear recoil scintillation efficiency



MicroCLEAN

- Two 20 cm photomultiplier tubes (PMTs) immersed in liquid to detect the light
- 20 cm diameter by 10 cm long teflon cylinder contains the active region
- As the scintillation light is in the UV, all inner surfaces coated with wavelength shifter (TPB) to convert to detectable blue light

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Calibration sources

- Several external gamma ray sources, including:
  - ^{57}Co - 122 keV
  - ^{133}Ba - 356 keV
  - ^{22}Na - 511 keV
  - ^{137}Cs - 662 keV
- D-D neutron generator provides 2.8 MeV monoenergetic neutrons to investigate nuclear recoils
  - Require coincidence with organic scintillator

Calibration sources

- There are a few problems with external gamma ray sources:
  - Energy is too high - WIMP signal is tens of keV
  - External - will not penetrate larger detectors because of self-shielding
  - Non-uniform - only illuminate one area of detector
- Can we fill the detector with a low energy source without increasing the backgrounds?

Calibration sources

- XENON10 used activated xenon isotopes to obtain uniform calibration at the end of their physics run in 2007 (Ni et al.) but:
  - Halflives on the order of a week, limiting repetition
  - Energies too high (164 and 236 keV)
  - Activation may have produced more long-lived isotopes that would increase the overall backgrounds

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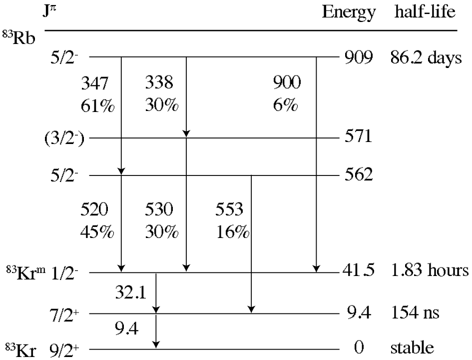
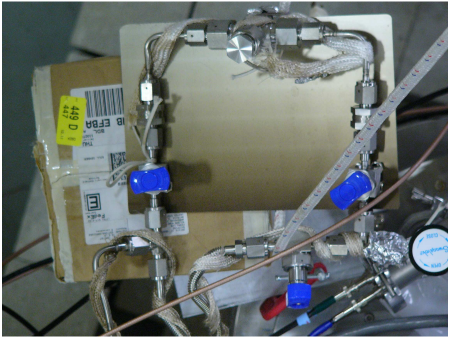
- An alternative is $^{83}Kr^{m}$, which decays with a half life of 1.83 hours
  - Produces two conversion electrons at 32.1 and 9.4 keV separated by 154 ns
  - Recently tested in xenon (Kastens et al., Manalaysay et al.), but might the krypton freeze out in argon or neon?

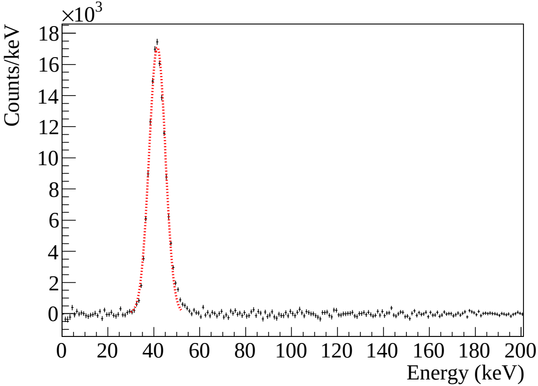
$^{83}Kr^{m}$ in argon

- A zeolite trap charged with ^{83}Rb - the ^{83}Rb decays with a half life of 86 days into $^{83}Kr^{m}$, which can escape the zeolite



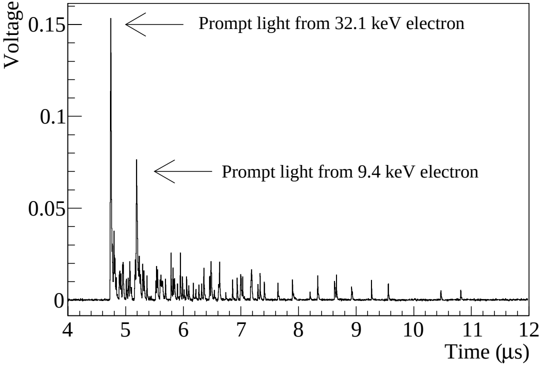


$^{83}\mathrm{Kr}^{\mathrm{m}}$ in argon



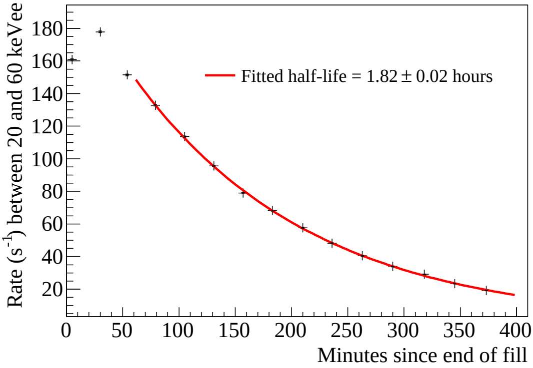
- Clear peak at 41.5 keV, $\sigma = 1.3 \times \sqrt{N_{pe}}$, with a rate of 170 Hz
- More than half the atoms produced in the trap get into the liquid

$^{83}Kr^{m}$ in argon



- The two conversion electrons are resolvable in the trace

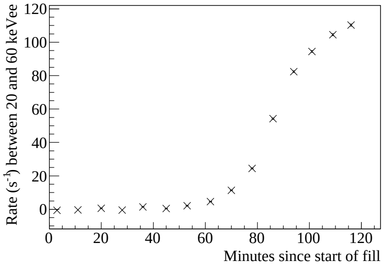
$^{83}Kr^m$ in argon

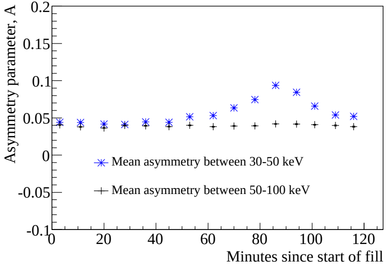


- Consistent with literature value for halflife of $^{83}Kr^m$, 1.82 ± 0.02 hrs

$^{83}Kr^{m}$ in argon

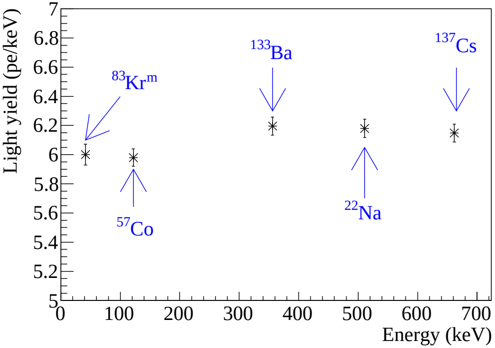
- Can we tell where the $^{83}Kr^{m}$ is in the detector?





Light yield and energy response

- Measure light yield with the $^{83}Kr^{m}$ peak of 6.0 ± 0.2 photoelectrons/keV
- Light yield vs. energy using the external gamma sources:



Lippincott et al., arXiv:0911.5453

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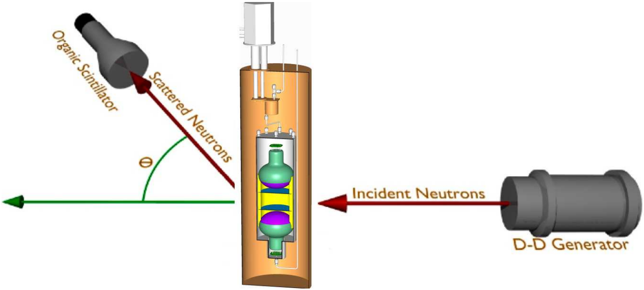
Nuclear recoil scintillation efficiency

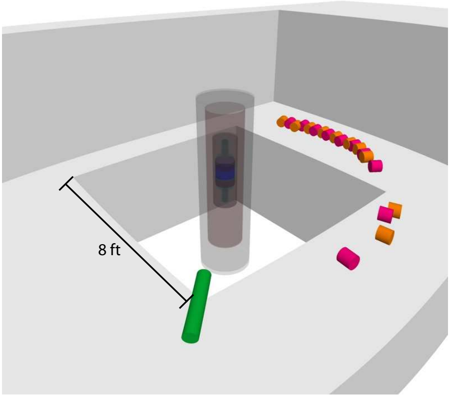
- Scintillation light from nuclear recoils is suppressed relative to electronic recoils of the same energy
  - Full microphysics of scintillation are not completely understood
  - Some energy in high density tracks is lost to heat - Lindhard effect
  - High density tracks can cause a reduction of excited atoms through collisions
  - Some ion-electron pairs never recombine, producing fewer molecules and less light
- Nuclear recoil scintillation efficiency (L_{eff}), in combination with PSD, sets the threshold of the detector

Nuclear recoil scintillation efficiency



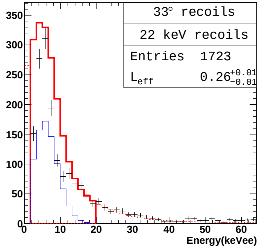
$$E_{recoil} = \frac{2E}{(1+A)^2}\left(1 + A - \cos^2\theta - \cos\theta\sqrt{A^2 + \cos^2\theta - 1}\right)$$

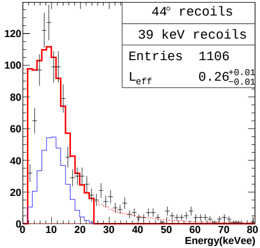
Simulations

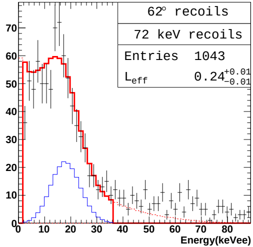


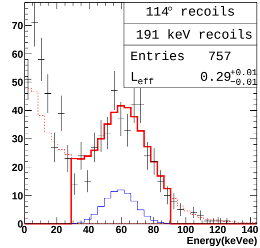
- Geant4 simulation to account for energy loss in multiple scattering
  - Multiple scattering in LAr
  - One scatter in LAr, one scatter in surrounding detector
- Output in scintillation photons per event and time-of-flight

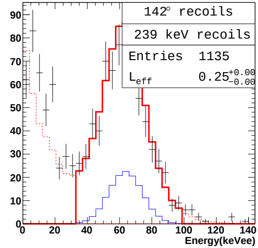
Preliminary results





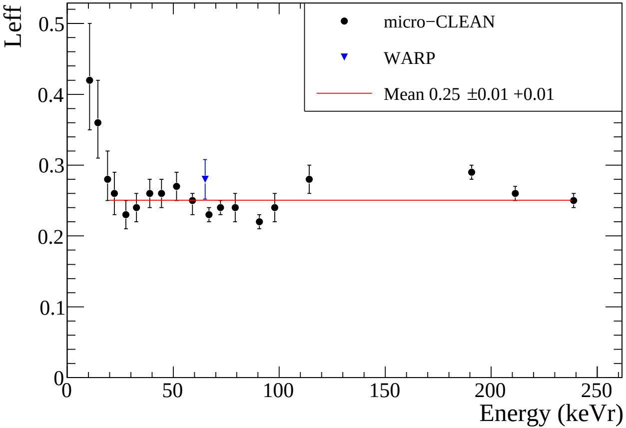






- Red is total simulation, blue is contribution from single scatters
- Data are fit to red histograms and scale factor gives L_{eff}

Nuclear recoil scintillation efficiency in argon



- Analysis ongoing
- Straight line fit between 30 and 100 keV returns $L_{eff} = 0.25 \pm 0.01$

Gastler et al., in preparation.

Nuclear recoil scintillation efficiency in argon

- Notation - “keVr” is the real energy of a recoil in the liquid
- “keVee” is the electron equivalent energy or “apparent” energy, as the calibrations are in general electronic recoils
- To convert from one to the other, multiply the energy in keVr by L_{eff} or divide energy in keVee by L_{eff}

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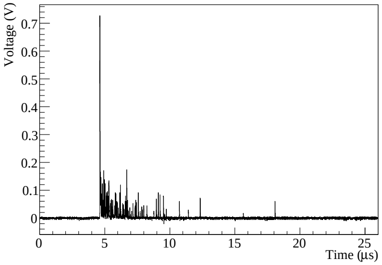
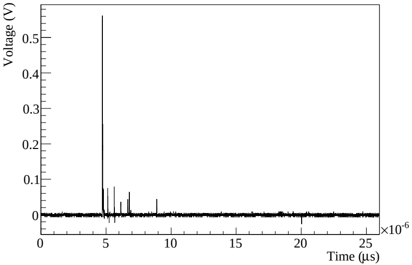
Pulse Shape Discrimination

- Nuclear and electronic recoils produce different ratios of singlet (prompt light) and triplet (late light) molecules

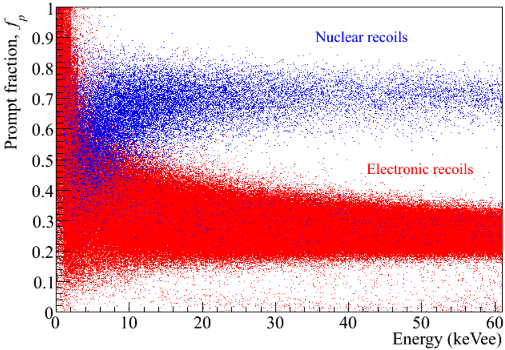


- Electronic recoil



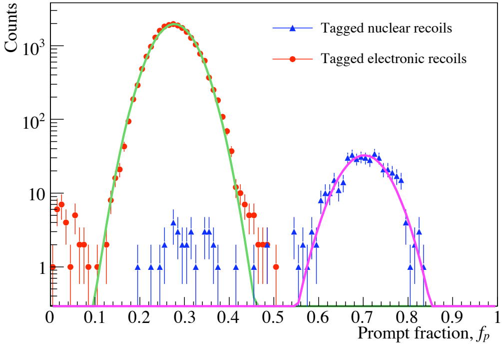
- Nuclear recoil

PSD methods - Prompt Fraction



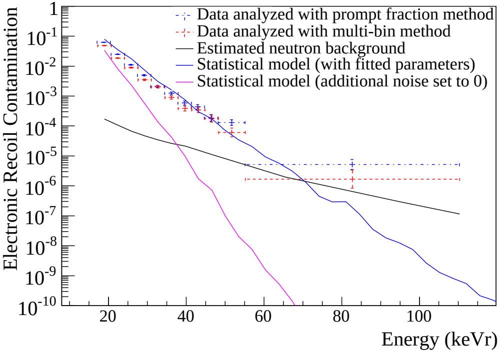
- Prompt fraction defined as the amount of light arriving in the first 90 ns divided by the total amount of light detected
    - A 90 ns window was chosen to optimize a Gaussian model of the prompt fraction, but the PSD is not very sensitive to choice of window

PSD methods - Prompt Fraction



- Project the previous plot onto the y-axis as a function of energy - can measure the prompt fraction distribution and the leakage
- Electronic recoil contamination (ERC) is defined as the probability of mistaking an electronic recoil for a nuclear recoil

Observed PSD



- We measure a background and statistics-limited ERC of 4.9×10^{-6} from 55-110 keVr with no contamination above 69 keVr using the prompt fraction method
- With a second method, the multi-bin method, we do about a factor of 3 better

Lippincott et al., PRC78:035801 (2008)

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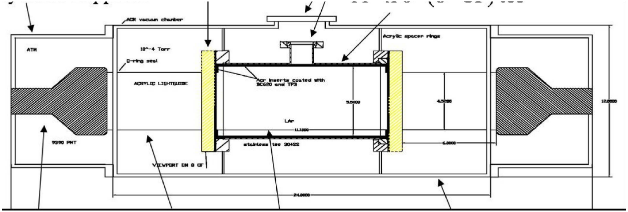
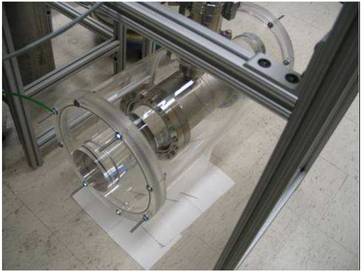
DEAP1

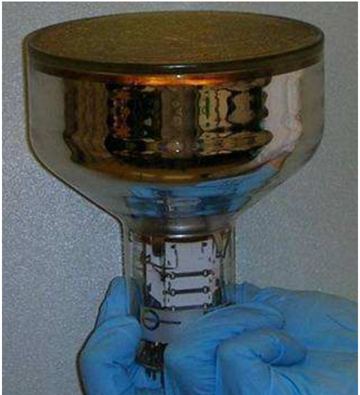
- DEAP1 is a similar detector to MicroCLEAN, trading light yield for lower backgrounds
- PMTs are outside of the cell, and look through acrylic light guides
  - Since PMTs are a major source of backgrounds (glass is radioactive), the acrylic serves as a passive shield
- Goals:
  - Demonstrate high statistics PSD
  - Understand background reduction - clean surfaces, low radon, etc.

DEAP1



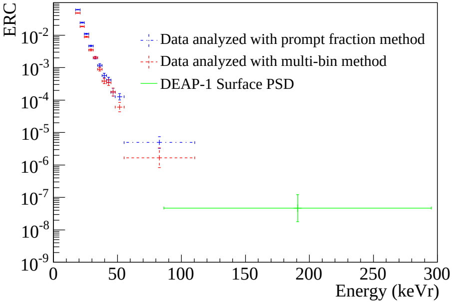
ACR vacuum chamber
ATM
10^-4 Torr
O-ring seal
ACRYLIC LIGHTGUIDE
Acr inserts coated with
BC620 and TPB
Acrylic spacer rings
LAr
11.1000
9390 PMT
VIEWPORT ON 8 CF
stainless tee 304SS
6.0000
24.0000
12.0000





DEAP1 PSD

- Run on surface at Queen's University in Kingston, Ontario
- Light yield of 2.8 pe/keV
- Used a ^{22}Na source with a tag of the 1274 gamma to reduce uncorrelated backgrounds
- Observed 1.7×10^{7} events between 40–80 keVee with no leakage



Boulay et al., arXiv:0904.2930v1 [astro-ph.IM]

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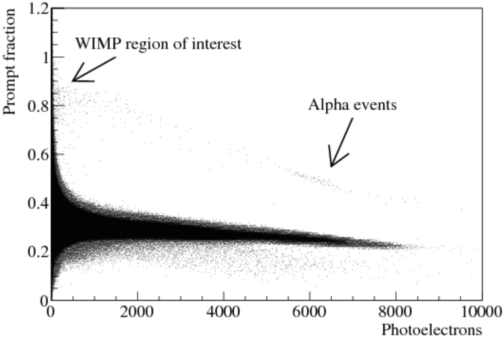
5 GAL/20 L
4G/Y32/S/07
USA/HEDWIN
BALTIMORE, MD
21211
Keep energized
80 psi
AIR LIQUIDE

Understanding backgrounds

- DEAP1 is now underground at SNO, in the old control room
- All surfaces cleaned to eliminate radon daughters
  - In first run from summer-fall 2008, we saw residual backgrounds from alpha contamination



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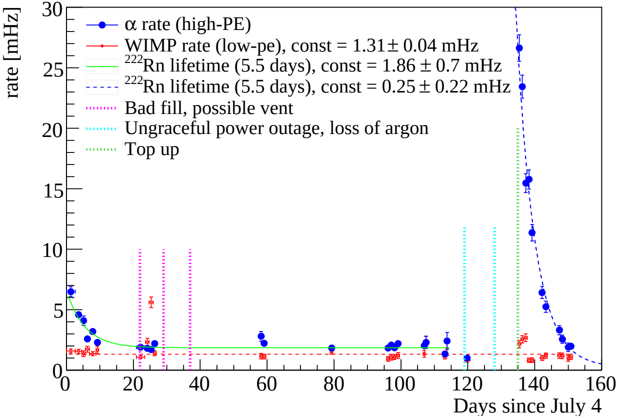
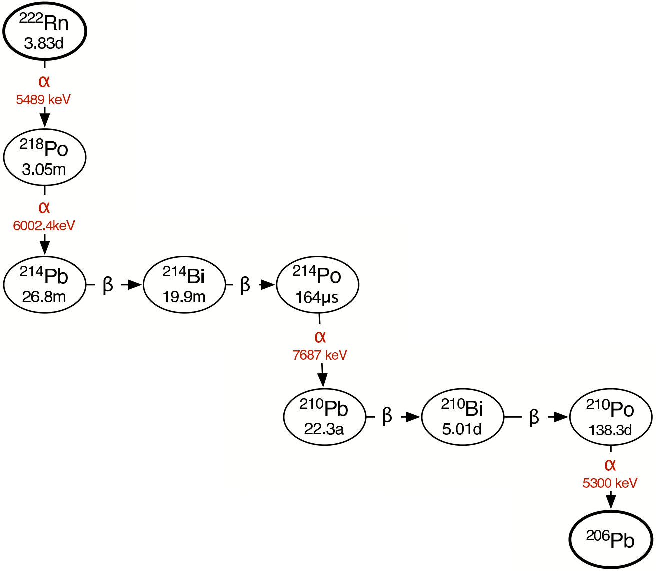


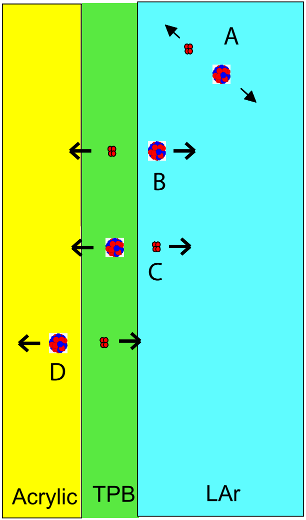
Radon



222Rn
3.83d
α
5489 keV
218Po
3.05m
α
6002.4keV
214Pb
26.8m
β
214Bi
19.9m
β
214Po
164μs
α
7687 keV
210Pb
22.3a
β
210Bi
5.01d
β
210Po
138.3d
α
5300 keV
206Pb

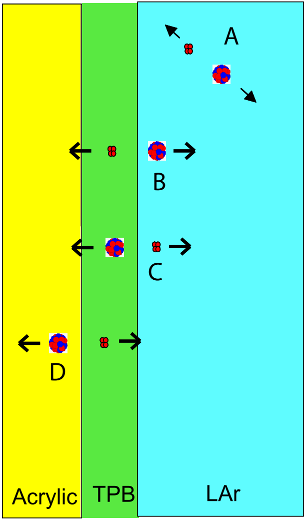
Why do we care?

- A - Event happens in the bulk, we see the alpha clearly



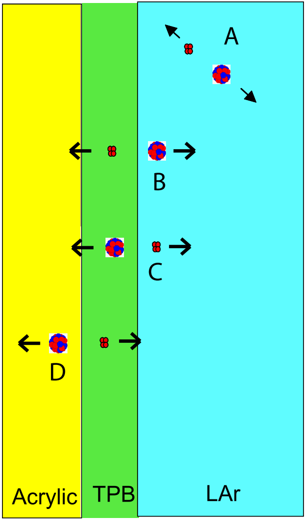
Why do we care?

- B - Event happens at surface, nuclear recoil enters bulk



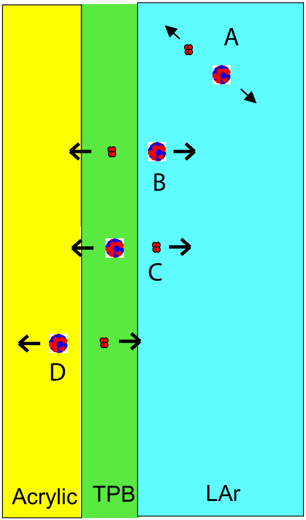
Why do we care?

- C - Event happens at surface, we see high energy alpha



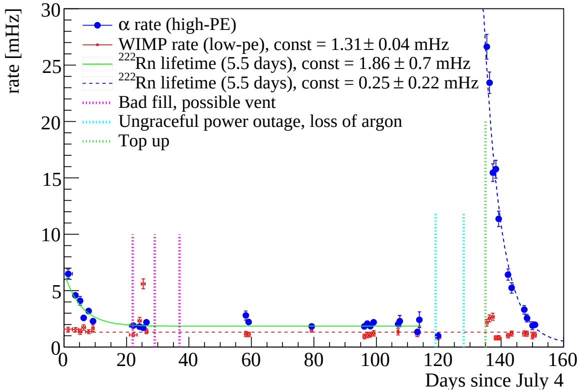
Why do we care?

- D - Event happens below TPB layer (or in the acrylic), we only see part of the alpha or part of the nuclear recoil



Understanding alpha backgrounds

- A clear component of ^{222}Rn that enters with the argon before decaying
- We see evidence for supported ^{222}Rn



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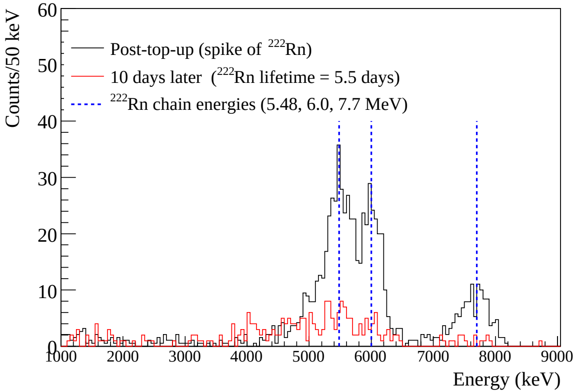
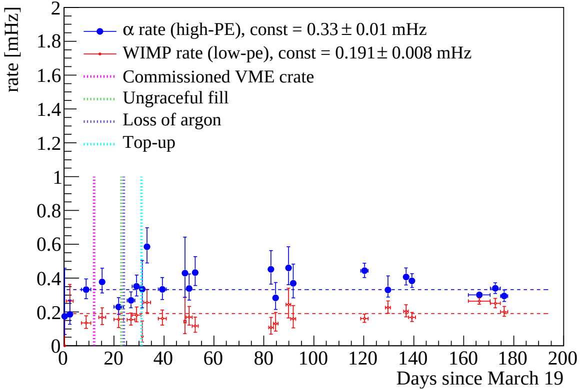


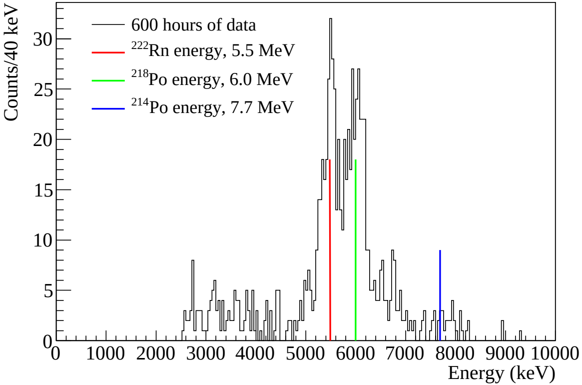
Alpha backgrounds - 2009 run

- A new chamber in operation from March-December 2009
  - Replaced reflective paint with teflon, recleaned surfaces
  - Argon passed through charcoal trap during fill to remove Rn

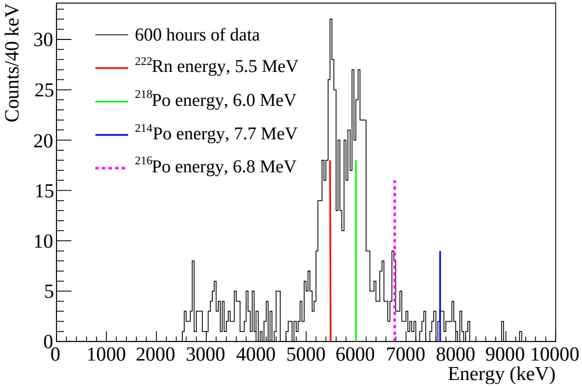


Alpha backgrounds - 2009 run

- 600 hours of background data



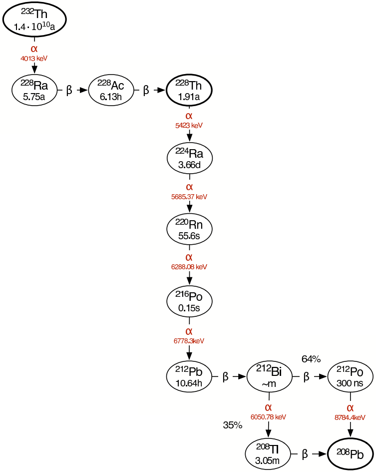
What is in our detector?



- There are methods to tag various components of this background
  - For example, there appears to be a peak at 6.7ish MeV
  - A Po daughter of ^{220}Rn in the thorium decay chain has that energy

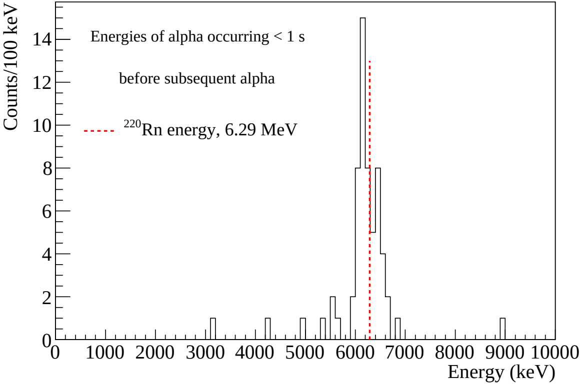
Tagging thorium chain using $^{220}Rn \rightarrow {}^{216}Po \rightarrow {}^{212}Pb$

- ^{216}Po has a 145 ms halflife - random coincidence rate is about 1 alpha every 2000 s



Tagging thorium chain using ^{220}Rn $\rightarrow$ ^{216}Po $\rightarrow$ ^{212}Pb

- There are $\sim$ 60 of these tagged events



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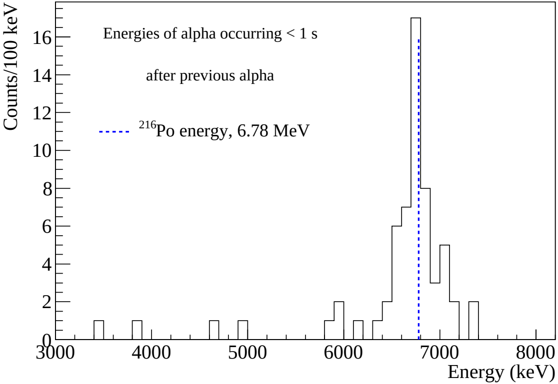

Where is the ^{220}Rn coming from then?

- How far can the radon atoms travel in 60 s?
- We checked over the plumbing, and it turns out there are some relatively hot ceriated welds
  - Radon emanation from the welds? Steel seems more likely...

Unanswered questions

- With the tag for ^{220}Rn and another for ^{222}Rn, we have accounted for roughly half the alpha activity - What is the other half?
  - ^{210}Po is an obvious candidate, and a rough estimation does show a peak at 5.3 MeV

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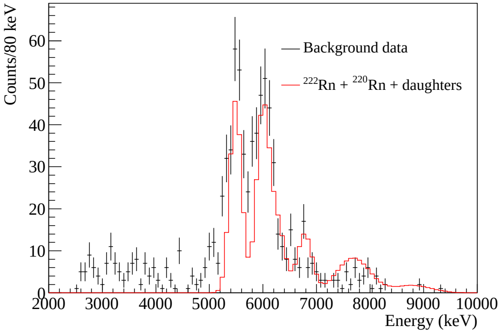

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- With the tag for ^{220}Rn and another for ^{222}Rn, we have accounted for roughly half the alpha activity - What is the other half?
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Unanswered questions

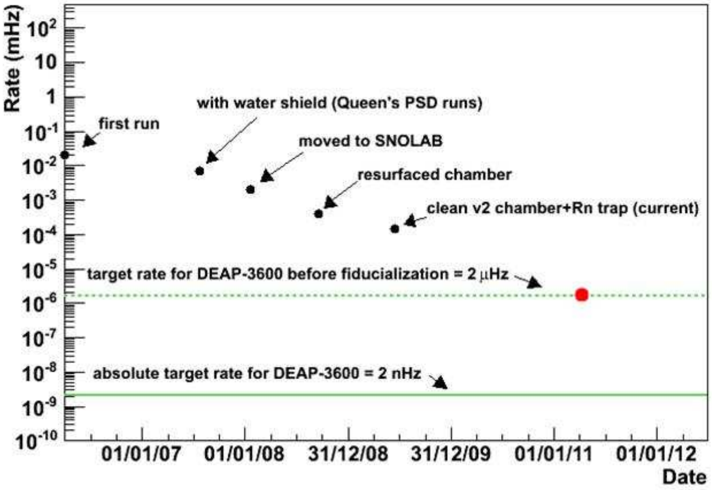
- With the tag for ^{220}Rn and another for ^{222}Rn, we have accounted for roughly half the alpha activity - What is the other half?
  - ^{210}Po is an obvious candidate
  - Degraded alphas from the acrylic and TPB layer seem the most likely candidates for the continuum below 5 MeV
- The new chamber reduced ^{222}Rn by a factor of 5 (hot paint), and other sources by a factor of 4.5

Source	Rate (mHz) in old chamber	Rate (mHz) in new chamber
All	2	0.4
^{220}Rn	0.030 ± 0.007	0.027 ± 0.004
^{222}Rn	0.17 ± 0.02	0.033 ± 0.006
^{210}Po plus	0.88	0.2

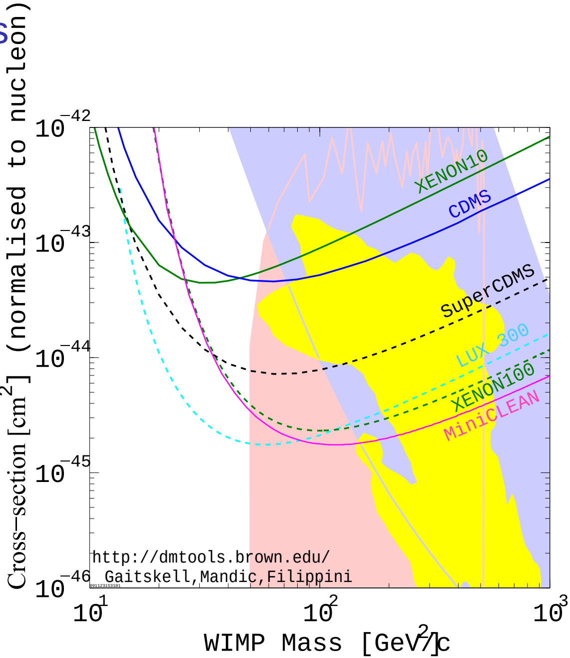
Unanswered questions

- We need more background reduction
  - Ultimately, we really care about the low energy backgrounds
  - The low energy rate also decreased from the old chamber to the new, so there is a connection
- New chamber under construction
  - Purification of TPB and removal of ^{210}Po from the acrylic

Backgrounds summary



Projections



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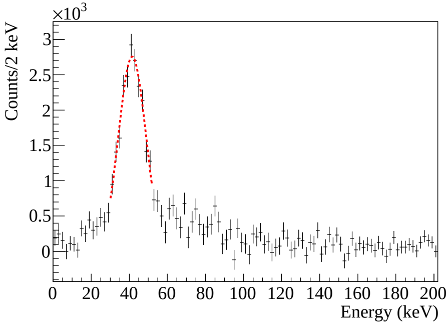
What is to be done

- Measure light yield
- Measure L_{eff}
- Measure PSD
- Can we detect pp neutrinos and dark matter with neon?

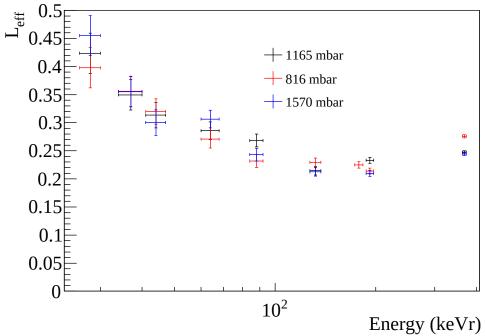
Neon results

- ^{83}Kr^{m} works in neon as well
- Measured light yield of 3 pe/keVee



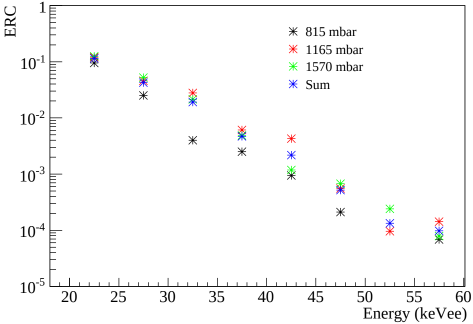
Neon results

- Nuclear recoil scintillation efficiency in neon



Neon results

- We've also measured PSD with the prompt fraction method



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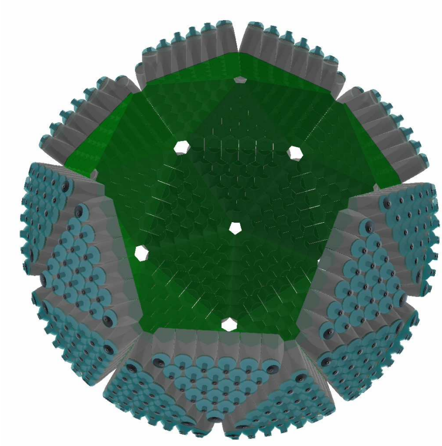
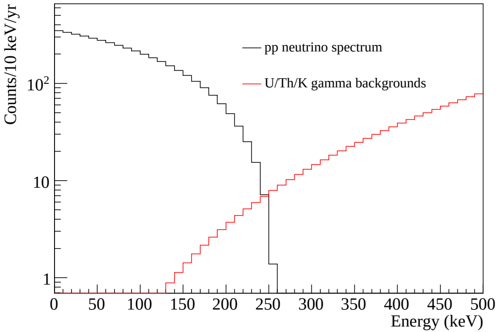
Next generation

- CLEAN (Big CLEAN)
  - 40-50 tonne detector with neon
  - Dark matter sensitivity plus a 1% measurement of pp neutrinos within 2 years



CLEAN simulations

- Primary pp-neutrino background - U/Th/K gammas from PMTs
- Simulated between 10-30 days of these backgrounds, projecting out to a full year
- Leakage into a 10 tonne fiducial volume ($R < 125$ cm) is 1% of pp-solar neutrino rate



CLEAN simulations

- Currently characterizing position reconstruction
  - Very preliminary studies show about 20 cm resolution at the fiducial radius
- Simulate other backgrounds and determine dark matter sensitivity

Summary

- MicroCLEAN
  - Light yield of 6.0 pe/keVee
  - Successful measurement of L_{eff}
  - Measured PSD at low energies, with background and statistics limited sensitivity of about 2×10^{-6}
  - Measurements repeated in neon
- DEAP1
  - Measured 6×10^{-8} PSD on surface
  - Now operating underground
  - Continuing to understand and eliminate backgrounds
  - Measure PSD to $< 10^{-8}$ in next few months
- MiniCLEAN, DEAP3600 (and CLEAN) are competitive dark matter detectors that will produce interesting results in the next few years

DEAP/CLEAN Collaboration

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Aksel Hallin
Boston University
Ed Kearns
Carleton University
Kevin Graham
Harvard University
John Doyle
Los Alamos National Laboratory
Andrew Hime
MIT
Joe Formaggio & Jocelyn Monroe
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Reyco Henning
University of Pennsylvania
Josh Klein
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University of South Dakota
Dongming Mei
SNOLAB
Fraser Duncan
Syracuse University
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TRIUMF
Fabrice Retrieve
Yale University
Dan McKinsey

End